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DETERMINING THE EFFECT OF LABORATORY TESTING CONDITIONS ON WORKING PARAMETERS OF THE ST-25 HALL THRUSTER

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The object of this study is the ST-25 Hall thruster with limited discharge power, no more than 200 W, designed by Flight Control LLC (Ukraine). The problem that was solved in the current paper was to determine the effect of residual gas pressure in vacuum chambers on the operating parameters of the Hall thruster. To solve this task, the operating parameters of the ST-25 thruster were determined, which was tested in three vacuum chambers with different sizes of residual pressure. As a result of the laboratory study into the operating parameters of the ST-25 thruster, the volt-ampere characteristics of the engine discharge at fixed values of the working gas (xenon) flow rate were obtained. The dependences of the engine thrust on the mass flow rate of the working gas at fixed values of the discharge voltage were derived. Based on the experimental data, the dependences of the specific impulse of the engine anode unit on the discharge voltage, as well as the dependence of efficiency of the engine anode unit on the discharge voltage were calculated. The studies showed that when the residual pressure in the vacuum chamber is reduced by 2–3 times, the operating parameters of the engine increase by 15–20 %. Such a reduction in residual pressure increases thrust by 25–40 %. Special feature of the results is the determination of threshold values of residual gas pressure in vacuum chambers during experimental studies, in which the operating parameters of the Hall thruster are similar to its operating parameters under space conditions. This work's findings could be used in practice when conducting experimental studies of electric rocket engines, when it is necessary to estimate the operating parameters of Hall thrusters that will be obtained under actual space conditions

Keywords: Hall thruster, residual pressure, engine thrust, specific impulse, engine efficiency

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1. Introduction

Measuring basic operating parameters of Hall thrusters – thrust force, amount of consumption of the working substance – is quite a difficult task, associated with the need to measure small amounts of thrust and small consumption of the working substance. Laboratory tests of Hall thrusters are carried out by different companies under different conditions: in vacuum chambers of different sizes and materials, with different vacuum pumping systems and the level of residual gas pressure, etc. Therefore, there is a need to determine the influence of the conditions of conducting laboratory tests of Hall thrusters on their main operating parameters, namely: thrust, specific impulse, and efficiency. At the company Flight Control LLC, three types of vacuum chambers are typically used for laboratory tests of Hall thrusters, which differ significantly in geometric dimensions, vacuum pumping systems, and the level of vacuum during research. Therefore, comparison of the measured and calculated values of the operating parameters of the Hall thruster ST-25, which were obtained under different conditions of laboratory tests, is of great interest. The results could help the developers and researchers of Hall thrusters to determine test conditions that would have a minor influence on the values of the engines' operating parameters. In this regard, conducting purposeful experimental studies on determining the influence of laboratory test conditions on the operating parameters of Hall thrusters is a relevant scientific topic of practical importance.

2. Literature review and problem statement

Many researchers believe that one of the most important tasks during ground tests of Hall thrusters is to determine the influence of the residual pressure in the vacuum chamber on the values of the engine's operating parameters. The collision of accelerated ions with the residual gas in the vacuum chamber leads to the fact that the operating parameters of the engine obtained under laboratory conditions differ significantly from the characteristics of the engine in outer space [1]. Residual gas entering the engine changes the operating parameters of the engine and affects its service life.

In [2], the results of a study of the characteristics of a Hall motor with magnetic shielding with a capacity of 20 kW and a centrally located cathode are reported. The study was conducted at two pumping speeds in a SITAEL IV10 vacuum chamber. The linear dependence of the discharge current and thrust depending on the mass consumption of the working substance was determined. In addition, the value of thrust and discharge current was always lower at lower values of residual gas pressure in the vacuum chamber.

The results of testing the effect of residual pressure on the characteristics of a 200 W Hall thruster are given in [3]. The increased residual pressure during ground tests significantly changes the engine parameters compared to the engine parameters in space. It is noted that the effect of residual pressure must be taken into account in order to better understand how the engine parameters will change in space. For four modes of engine operation, the dependences on the background pressure in the vacuum chamber are determined and it is shown that the engine parameters increase when the background pressure decreases.

In [4], the results of the development of an analytical model of the influence of the object's background flow on the parameters of the 5 kW P5, 6 kW H6. and 1.5 kW SPT-100 Hall thrusters are given. It is shown that the constructed models are 40–70 % closer to empirical measurements. The results show that the developed analytical background flow model is an effective forecasting tool for neutral absorption calculations. The results reported in the paper quite fully reflect the influence of test conditions on the operating parameters of engines with a fairly large power (1.5–6 kW), but this model is practically impossible to use for analyzing such an influence on the parameters of engines with a fairly low power of up to 200–300 W.

Vacuum parameters during laboratory studies can affect not only the parameters of the plasma beam but also the internal processes in the Hall thruster. In order to test this hypothesis, measurements of the distribution of ion velocities in the acceleration channel of the engine were carried out using laser-induced fluorescence [5, 6]. These studies showed that an increase in the residual pressure of the gas in the vacuum chamber shifts the region of ion acceleration up the acceleration channel, which leads to a broadening of the distribution of ion velocities and energies. In addition, with an increase in the residual gas pressure in the vacuum chamber, an increase in the fluctuations of the engine discharge current was recorded. But the use of laser-induced fluorescence is not available to most Hall thruster research and development laboratories, including Flight Control. Therefore, it was decided to conduct experimental studies into the operating parameters of the ST-25 thruster.

Paper [7] reports the results of studying the influence of laboratory test conditions on the speed and amount of erosion of structural elements of the Hall thruster. It defines the resource of its operation, but no information about the operating characteristics of the engine was given. The determination of the temperature conditions of the Hall thruster operation is given in [8] but the results do not make it possible to compare the operating parameters of the engine operating under different temperature conditions.

Based on our critical review of the literature [1–8], it was determined that the above works lack information on the influence of test conditions on the operating parameters of Hall thrusters – thrust, specific impulse, and efficiency. Thus, this problem has not yet been solved and most designers of Hall thrusters are faced with this problem. All this allows us to state that conducting research to determine the influence of residual gas pressure in the vacuum chamber on the operating parameters of Hall thrusters is expedient.

3. The aim and objectives of the study

The purpose of our work is to determine the effect of residual gas pressure in the vacuum chamber on the operating parameters of the Hall thruster through experimental research. This will make it possible to determine the conditions for testing Hall thrusters that provide sufficient accuracy in determining the value of thrust, specific impulse, and overall efficiency of the engine.

To achieve the set goal, it was necessary to solve the following tasks:

– to experimentally determine the volt-ampere characteristics and the dependence of engine thrust on the consumption values of the working substance in different vacuum chambers and at different values of residual gas pressure;

– to define the calculation dependences of the specific impulse and efficiency of the engine on the discharge voltage.

4. The study materials and methods

The ST-25 Hall thruster was used as an object of research [9, 10]. The hypothesis of the study was the assumption that the conditions of conducting laboratory studies significantly affect the operating parameters of the Hall thruster. To determine the influence of laboratory test conditions on the operating parameters of the engine, experimental studies were conducted in three different vacuum chambers (Fig. 1–3), which differed significantly in terms of their dimensions and level of residual vacuum during laboratory tests. The basic parameters of vacuum chambers are given in Table 1.

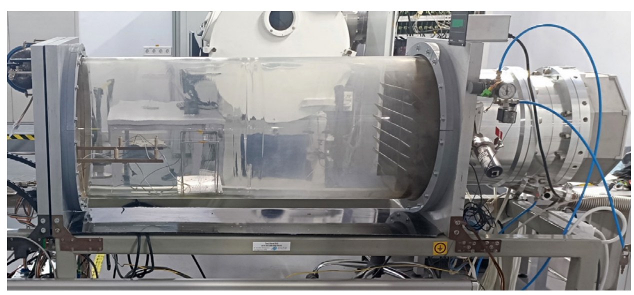

Fig. 1. General view of vacuum chamber No. 1

Fig. 2. General view of vacuum chamber No. 2

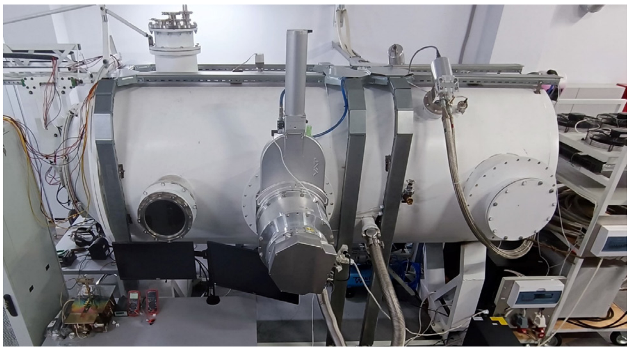

Fig. 3. General view of vacuum chamber No. 3

Table 1

Technical parameters of vacuum chambers

No.	Parameter	Chamber 1	Chamber 2	Chamber 3
1	Dimensions, mm (length/diameter)	1000/380	1350/750	4000/1300
2	Pump capacity, l/s	2200	6400	33600
3	Pressure at mass flow rate of xenon 0.7 mg/s, Torr	$(2–3)\cdot10^{-4}$	$(1–2)\cdot10^{-4}$	$(7–8)\cdot10^{-5}$
4	Body material	Glass, aluminum	Stainless steel	Stainless steel

A laboratory supply system was used to supply, control, and register the mass flow rate of the working fluid into the anode module of the engine and the hollow cathode. The accuracy of supplying working gas to the engine was ±3 %. Stabilization and regulation of working gas flow in the laboratory supply system was carried out by adjustable valves by the Bronkhorst company FG-201CV-AAD-33-V-AA-000, both through the working gas supply channel to the anode and to the hollow cathode.

The following power sources were used during laboratory research:

1. Regulated discharge voltage source – TDK Lambda GEN600-2.6.
2. The source of stable current for powering the motor electromagnet coils – Uni-T 3315TFL-II.
3. Current source for initial heating of the cathode – Matrix MPS-3010L-1.
4. The voltage source of the cathode keeper – Delta D400.

Studies into the operation parameters of the ST-25 thruster were carried out at different values of the discharge voltage and the mass flow rate of the working gas into the anode module of the engine in three different vacuum chambers.

Research was carried out using a procedure that involved turning on and off the engine according to a standard cyclogram. During the research, electrical parameters (discharge voltage and current), thrust, and consumption of the working substance to the anode module and cathode were recorded.

To ensure the reliability of information regarding the object of research, planning of experiments was carried out, which were considered as multifactorial.

Discharge voltage and working substance flow rate to the anode unit of the engine were considered as the most significant factors when conducting studies of engine operating parameters. As a result of experimental studies, the following operating parameters were determined: maximum thrust, specific impulse, coefficient of useful action of the anode unit. The listed parameters fully determine the efficiency of the engine and the degree of optimization of its parameters.

Fig. 4 shows the input signals that were applied to the engine during the research, as well as the output signals and calculated parameters of the engine, which were obtained as a result of the processing of experimental studies.

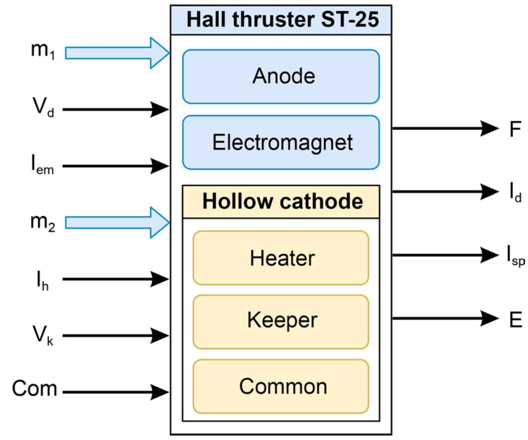

Fig. 4. Input and output variables and calculated parameters of the ST-25 thruster: V_d, I_d – voltage and discharge current; I_{em} – motor electromagnet current; V_k is the voltage of the keeper of the hollow cathode; I_h – cathode heater current; m_1, m_2 – flow rate of working gas in the anode module and cathode; F – thrust; I_{sp} – specific impulse; E – efficiency factor of the anode unit

During the experimental research, the thrust measurement of the engine was carried out with a specially designed and calibrated thrust measuring device, which provides measurement of the thrust value in the range from 5 to 15 mN with an error that does not exceed ±4 %.

Research was carried out for each mode of operation of the engine, by setting the discharge voltage and the corresponding working gas flow rates. The discharge voltage was set by a stabilized voltage source in the range of 250–350 V with a step of 25 V. The mass flow rate of the working gas in the anode module was set in the range of 0.5–0.8 mg/s with a step of 0.1 mg/s.

The processing of research results for each cycle of measurements was carried out using the methods of mathematical statistics. Statistical treatment of experimental data for each given engine operating mode was performed as follows:

a) registration of engine parameters for 15 minutes with an interval of 5 minutes;

b) calculation of average values of each parameter;

c) determination of measurement errors of each parameter.

As a result of the experimental data processing, the average values of the discharge current and the magnitude of the thrust were obtained with an error value that does not exceed ±5 % of the average value. Other engine parameters were calculated on the basis of the average values of the discharge current and the amount of thrust.

5. Results of investigating operating parameters of the ST-25 thruster in various vacuum chambers

5. 1. Experimental determination of the volt-ampere characteristics and the dependence of engine thrust on the working substance flow rate

During the experimental studies, the volt-ampere characteristics of the gas discharge of the ST-25 thruster were determined in different vacuum chambers with different values of the residual gas pressure, which are shown in Fig. 5–7. Analysis of the resulting volt-ampere characteristics reveals that the average value of the discharge current at different values of the residual pressure in the vacuum chambers remains almost unchanged and is determined by the flow rate of the working gas into the anode unit of the engine.

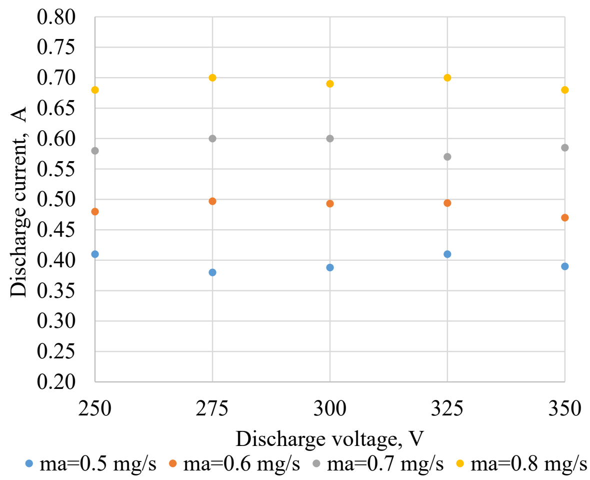

Fig. 5. Volt-ampere discharge characteristics in vacuum chamber No. 1

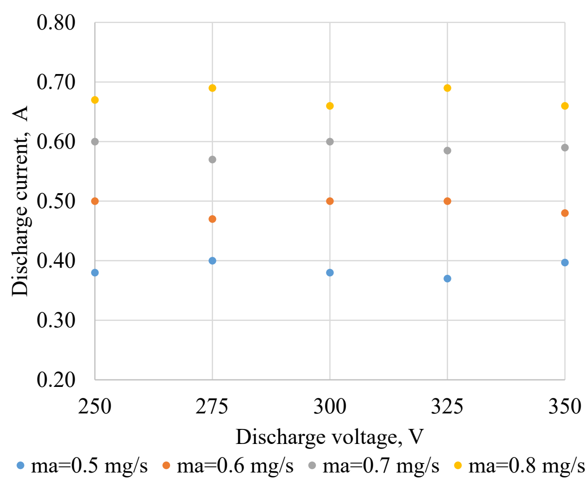

Fig. 6. Volt-ampere discharge characteristics in vacuum chamber No. 2

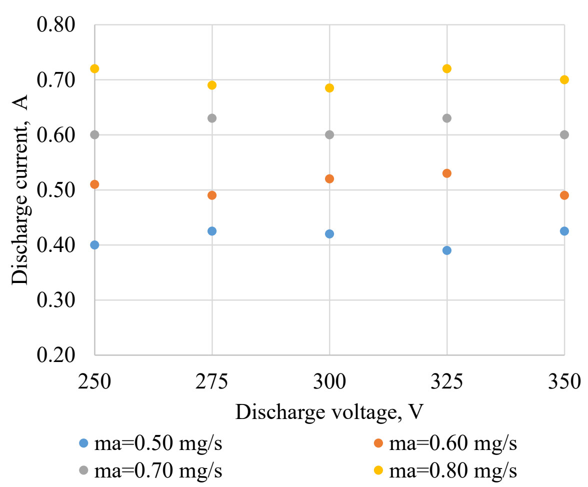

Fig. 7. Volt-ampere discharge characteristics in vacuum chamber No. 3

Dependences of the engine thrust on the mass flow rate of working substance, obtained during the operation of the ST-25 thruster in different vacuum chambers at different values of the residual pressure, are shown in Fig. 8–10.

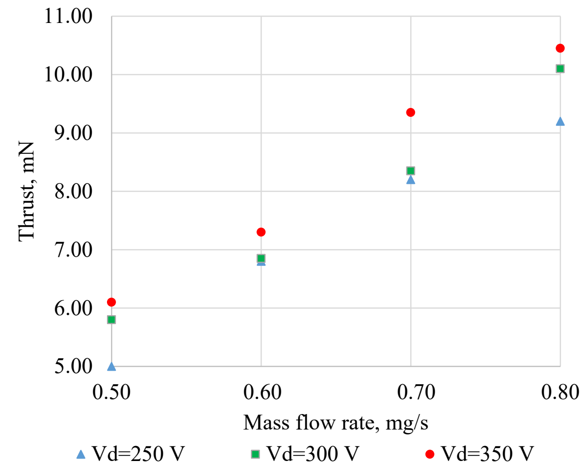

Fig. 8. Dependence of thrust on the mass flow rate of the working gas in vacuum chamber No. 1

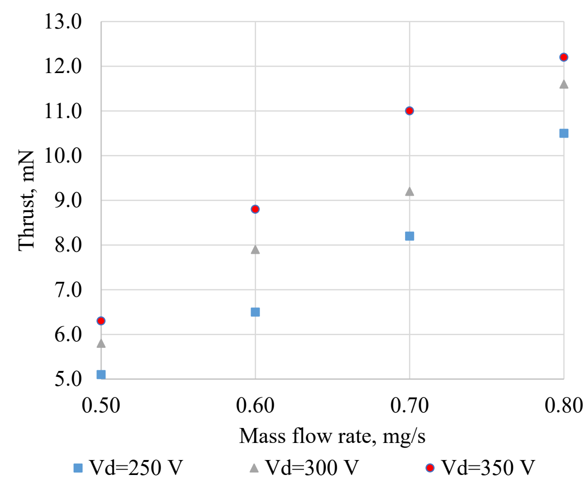

Fig. 9. Dependence of thrust on the mass flow rate of the working gas in vacuum chamber No. 2

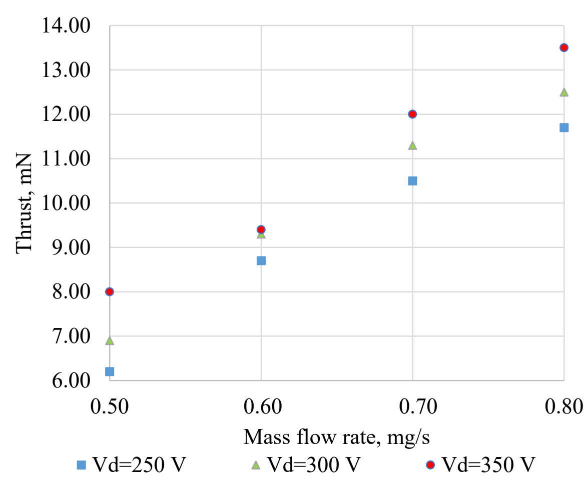

Fig. 10. Dependence of thrust on the mass flow rate of the working gas in vacuum chamber No. 3

Our experimental data show that despite the same values of the discharge currents obtained in different chambers, the thrust values of the engine increase when the residual gas pressure in the vacuum chamber is reduced by 25–40 %. From this it can be concluded that the experimental measurements of thrust of the engine, obtained at a high residual pressure in the vacuum chamber, are significantly underestimated.

5. 2. Determining the dependence of specific impulse and efficiency of the motor on discharge voltage

Based on the results of experimental tests of volt-ampere characteristics and engine thrust, the dependences of the specific impulse of the anode unit on the discharge voltage and the working substance mass flow rate were calculated. The plots of calculated dependences for engine operation in different chambers are shown in Fig. 11–13.

These figures show the calculated dependences according to the following formula [9]:

$$I_{spa} = \frac{F}{\dot{m}_a \cdot g}, \qquad (1)$$

where I_{spa} is the specific impulse of the anode module of the engine, F is the thrust, $\dot{m}_a$ is the mass flow rate through the anode module.

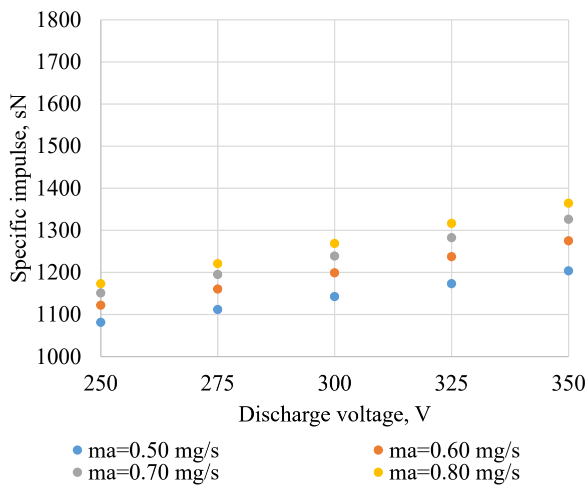

Fig. 11. Dependence of the specific impulse of anode module of the engine on discharge voltage in vacuum chamber No. 1

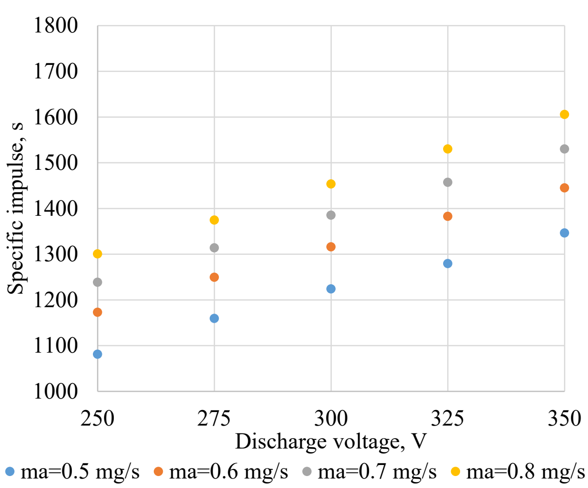

Fig. 12. Dependence of the specific impulse of anode module of the engine on discharge voltage in vacuum chamber No. 2

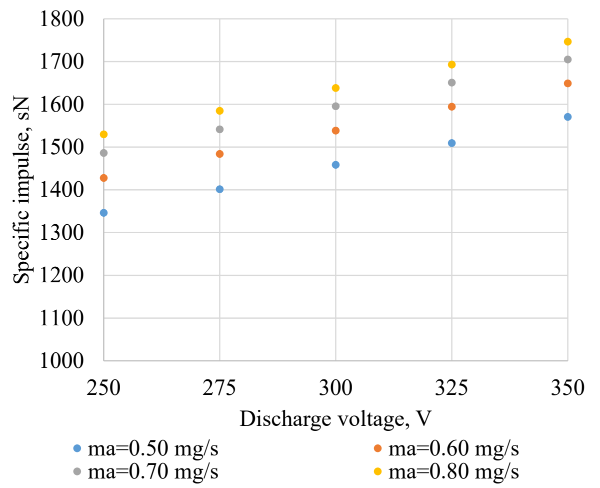

Fig. 13. Dependence of the specific impulse of anode module of the engine on discharge voltage in vacuum chamber No. 3

Dependences of the value of anode efficiency on the discharge voltage and the amount of the working substance flow rate during engine operation in different chambers are shown in Fig. 14–16.

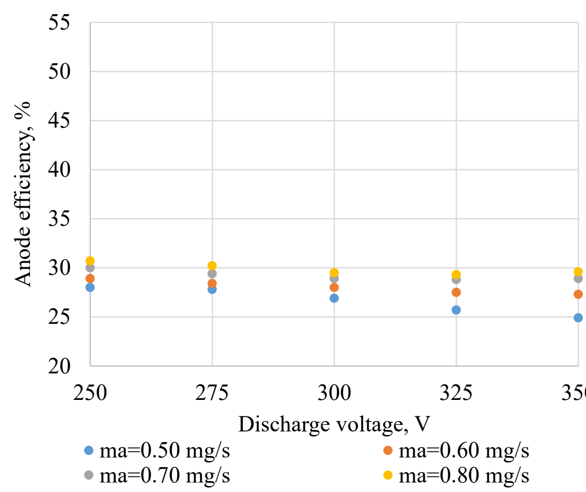

Fig. 14. Dependence of the efficiency of anode module of the engine on discharge voltage in vacuum chamber No. 1

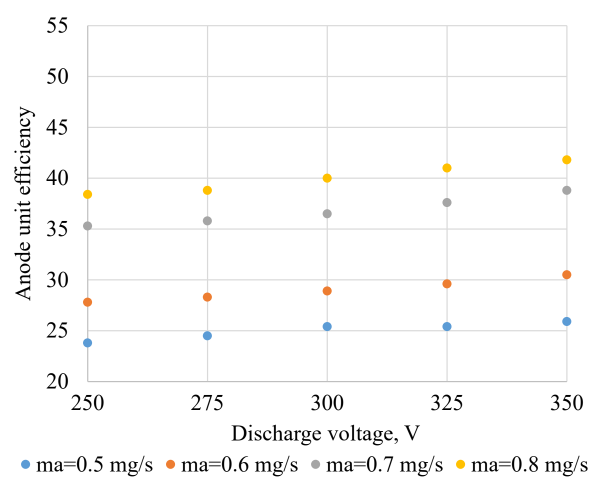

Fig. 15. Dependence of the efficiency of anode module of the engine on discharge voltage in vacuum chamber No. 2

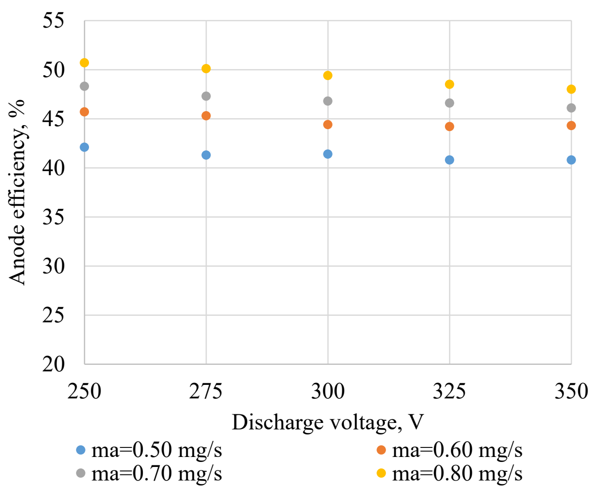

Fig. 16. Dependence of the efficiency of anode module of the engine on discharge voltage in vacuum chamber No. 3

These figures show the calculated dependences according to the following formula:

$$\eta_a = \frac{F^2}{2 \cdot \dot{m}_a \cdot N_d} \cdot 100. \qquad (2)$$

Analysis of the data shown in Fig. 11–16 makes it possible to conclude that when the ST-25 thruster is operating in the range of discharge voltage 250–350 V and working gas mass flow rate 0.5–0.8 mg/s, the values of anode efficiency and anode specific impulse significantly depend on the value of residual pressure in vacuum chambers.

6. Discussion of results from determining the operating parameters of the ST-25 thruster during its operation in various vacuum chambers

As a result of our research, experimental (Fig. 5–10) and calculated (Fig. 11–16) data were obtained regarding the effect of residual pressure in vacuum chambers on the operating parameters of the ST-25 Hall thruster – thrust, discharge current, specific impulse, and efficiency. The research results generally coincide with the data obtained by researchers of other engines [1–8] under other conditions of laboratory studies. The feature of our results (Fig. 5–10) is that specific quantitative data were obtained regarding the effect of residual pressure on the operating parameters of the engine. Namely, improving the vacuum by 2–3 times during laboratory studies of the ST-25 thruster led to an increase in the values of its operating parameters by 15÷20 % (Fig. 11–16). Thus, in order to compare the operating parameters of Hall thrusters by different designers, it is necessary to take into account the conditions of laboratory research of the engines, first of all, the value of residual pressure in the vacuum chamber.

The current study has certain limitations, due to investigating the characteristics of the ST-25 Hall thruster with a limited discharge power, no more than 200 W. This means that the results obtained may not be the same or not applicable to higher power engines. When studying more powerful engines, it is more difficult to achieve the minimum required residual pressure in the vacuum chamber. This is due to higher working substance flow rate and other factors that can affect the operating parameters of the engine. Thus, the limitations of this study are the lack of research results on determining the impact of test conditions of engines of greater power and taking into account the peculiarities of the increase in the working substance flow rate.

The shortcomings and limitations of our research also include the lack of determination of the relationship between the operating parameters of the Hall thrusters and the geometric dimensions and materials of the vacuum chambers in which the research was conducted. It is quite likely that the conditions of neutralization of the engine's ion beam greatly affect the work of the cathode, and thereby the ionization processes to accelerate the formed ions. This dependence should be especially evident for small vacuum chambers. But we hope to conduct these studies during further experimental tests.

Further advancement of the current research involves conducting similar studies for the ST-40 Hall thruster (discharge power – up to 600 W) and ST-100 (discharge power – up to 1500 W). Difficulties that may arise along the way are achieving the minimum required residual pressure in the vacuum chamber for the ST-100 engine.

7. Conclusions

1. As a result of our experimental studies, it was shown that the volt-ampere characteristics of the ST-25 thruster discharge practically do not depend on the value of residual pressure in the vacuum chambers. At the same time, experimental studies revealed the existence of a significant dependence of engine thrust on test conditions. Our studies have shown that reducing the residual pressure by 2–3 times in the vacuum chamber increases thrust by 25–40 %.

2. The operating parameters of the Hall thrusters obtained as a result of calculations, namely, values of the specific impulse and efficiency of the anode module of the ST-25 Hall thruster, also increase by 15–20 % when the residual pressure in the vacuum chambers decreases.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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The research was carried out within the framework of designing the SPS-25 electric rocket propulsion system by Flight Control LLC, a division of Space Electric Thruster Systems (SETS).

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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